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Biogas production and changes in soil carbon input - A regional analysis

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ABSTRACT

The inclusion of biogas production into the agricultural system has modified crop management and as a result the soil organic carbon (SOC) cycle of the agricultural landscape. To evaluate the effects for the German federal state of Saxony this study determines: (1) the share of agricultural land required for biogas production, (2) the change in regional carbon input fluxes to soil during the time of the establishment of the biogas production considering also the quality of sources of different fresh organic matter (FOM) for the formation of SOC and (3) the differences in carbon input to SOC between the area influenced by biogas production (here "biogas fingerprint area" (BFA)) and the surrounding arable land.

Based on the location of biogas plants the region was subdivided into biomass providing units (BPUs) where a part of the arable land was considered as affected by biogas production (BFA). We hypothesized that each biogas plant uses a specific substrate mix according to its capacity. The carbon fluxes for each BPU were estimated for the years 2000 (without biogas plants) and 2011 (with biogas plants). For the year 2011, the analysis included the area demand for production of biogas feedstock and digestate recycling.

On average 17.6% of the BPU agricultural land was required to supply the biogas plants and dispose of their digestate. Per kilowatt installed electrical capacity this equates to 2.0 ha, including inter alia 0.4 ha for energy crops. Highest area requirements have been observed for biogas plants with < 500 kW installed capacity. Between 2000 and 2011 the total carbon flux into soil increased by 2.1%. When considering the quality of different FOM sources the gain in carbon input was 2.8%. The BFAs showed higher carbon input to soil than the surrounding agricultural land due to high contributions from digestate and crop residues (esp. agricultural grass). This compensated the low carbon input from crop by-products (e.g. straw).

1. Introduction

Soil is one of the most important and most complex natural resources and is an essential contributor to the global ecosystem, providing a regulatory system that supports a multitude of ecosystem functions and services (Podmanicky et al., 2011; Garrigues et al., 2012; Adhikari and Hartemink, 2016). Soil organic matter (SOM) and its major component soil organic carbon (SOC) are fundamental to soil and its ecosystem functions in particular the sequestration of carbon (Podmanicky et al., 2011; Campbell and Paustian, 2015; Yigini and Panagos, 2016).

Biogas production within conventional agricultural systems has been promoted as an integrated approach to support nutrient cycling, while mitigating greenhouse gases emissions from conventional fossil energy production. Germany is the largest biogas producer in the European Union, with almost 8700 biogas plants installed in 2016 (Daniel-Gromke et al., 2017, 2018). A previous study by Franko et al. (2015), for the region of Central Germany, identified a number of hot spots where the usage of carbon may raise a conflict between sustaining SOC and producing bioenergy. The expansion of the agricultural system to include bioenergy production has resulted in an adaption of the agricultural management (e.g. cultivated crops, digestate application instead of slurry), which in turn has changed the carbon input to soil within these agricultural landscapes. At the same time biogas

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production is heavily influenced by the regional availability and variability of feedstock.

To date, no general approach has been developed to understand the potential influence of bioenergy production on regional soil carbon cycling. It is a challenge to tackle the additional complexity which biogas production can introduce into agricultural systems (Arthurson, 2009; Möller and Müller, 2012; Barbosa et al., 2014). Therefore, the aim of this study was an ex-post evaluation of the biogas production within the agricultural landscape of a case study region. For each biogas plant within the federal state of Saxony we estimated the agricultural area required for the provision of biogas feedstock and recycling of digestate, proposing the combination of this as “biogas fingerprint area” (BFA) of a biogas plant. The carbon input to arable soil has been estimated for two separate years 2000 (without biogas production) and 2011 (with biogas production). Here also the quality of different sources of fresh organic matter (FOM) regarding the formation of new SOC was considered. Furthermore, for the year 2011 we compared the carbon input on the BFAs and the arable land not affected by biogas production.

2. Material & methods

2.1. Spatial units of investigation

The federal state of Saxony, in East Germany was used as the study region. During the last decade a rapid development of the biogas industry has been observed in this area (Grunewald, 2012). For regional subdivision of Saxony and main spatial element of the study we used ‘biomass providing units’ (BPU) which separate catchment areas (i.e. for agricultural substrates) from competing biogas plants as defined by Franko et al. (2015). The location and capacity of the biogas plants within Saxony were determined by Das et al. (2012). Relevant cropping and livestock data was aggregated to the BPU level.

We assumed that every BPU had a closed matter cycle regarding agricultural substrates in the context of biogas production. The feedstock demand of a biogas plant was supplied by the agricultural area within the associated BPU, with the biogas digestate being returned to the same area. The agricultural land required for the production of biogas feedstock and disposal of digestate was defined as “biogas fingerprint area” (BFA) of a BPU (Section 2.4). The soil related carbon flows within the BFAs are assumed to differ from the surrounding agricultural land (Section 2.5). It was hypothesized that depending on the installed electrical capacity and the feedstock mix of the biogas plant, as well as the regional agricultural parameters (e.g. crop mix and yields, livestock mix, management of the arable land), every biogas plant will have its own unique BFA.

For each BPU the associated land use considerations are shown in Fig. 1. The crop mix of the BFA corresponds to the direct and indirect demands for biogas feedstock. Depending on the fertilization intensity, the agricultural area needed for the application of digestate may be smaller or larger than the area for production of biogas feedstock. If the area needed is larger, an additional area for the application of biogas digestate was considered to be necessary. Prior to the implementation of biogas production, livestock excrement were applied to all arable land (year 2000). However, with the installation of biogas plants (year 2011), it was assumed that excrement not used for biogas production were applied only to the BPU area outside of the BFA.

2.2. Regional agricultural parameters

2.2.1. Land use and agro-economic regions

The federal state of Saxony (approx. 18,400 km^2) is dominated by arable land-use (Fig. 2). Due to the very fertile loess soils, which cover a large part of the study area, 52% of the region is used for agricultural purposes. Saxony can be subdivided into three main “agro-economic regions”, based on characteristics of soil, landscape characteristics and their associated agricultural activities (LfL, 1999). These include: (1) Saxon heath and pond landscape, (2) Saxon loess region, (3) Saxon low mountain range and foreland. For more information see supplementary material (Table A1).

2.2.2. Crop harvest areas and yield

Data on crop harvest areas and crop yield for 20 different crops as well as catch crops have been provided by the ‘State Agency for the Environment, Nature Conservation and Geology of Saxony’ (LfULG). Crop harvest areas are derived from statistics on municipality level (year 2000) and InVeKoS data (Integriertes Verwaltungs- und Kontrollsystem) for the year 2011. Crop yield data was based on analysis of the software BEFU, a fertilization advisory system used by Saxon farmers (Förster, 2013). Essential crops included in the analysis, as well as their average areal share and yield for the period 2000–2011 are shown in Table 1. For these years cereals were found to be the dominant crops (58%) in Saxony, followed by winter rape (15%) and maize for silage (9%).

Non-harvested biomass was characterized into two groups, crop residues and crop by-products, −based on the potential usage of the material (see also Section 2.5). While residues like crop roots and stubble were assumed to be left on the field, the fate of by-products depends on farmers decision: by-products (i.e. straw) can be left on the field or carried away to be used as litter for the livestock stable or sold on the market. Based on expert knowledge, at the state agency LfULG, it was assumed that by-products of relevant crops were removed from approx. 20% of the arable area.

2.2.3. Excrement

We calculated the amount of excrement available for field application or biogas production ($excr_{av}$ in $t\,a^{-1}$) based on livestock statistics on district and municipality levels (StLa, 2016a, 2016b). Therefore the total amount of excrement produced from all livestock was corrected for the amount that is left on pasture during grazing (StLa, 2012a). For each animal group i the specific average annual amount of excrement ($excr_i$ *in* $t\,a^{-1}$; LfULG, 2015), the share of grazing time within one year ($grzt\ [-]$) and the number of individuals within this group (n) was used to calculate the amount of excrement which we assumed to be slurry:

$$excr_{av} = \sum_i (n_i \bullet excr_i \bullet (1 - grzt_i)) \tag{1}$$

The data was aggregated from municipality level to BPU level using the areal share of municipalities in the BPUs. Within the BPUs the excrement not used for the production of biogas was assumed to be equally distributed on arable land outside of the BFA.

2.3. Profile of regional biogas plants

2.3.1. Deriving representative feedstock mixes

The substrate mix used for the production of biogas can vary widely between individual biogas plants making it difficult to parameterize in large scale assessments. Therefore, the demand for biomass substrate was estimated using the approaches outlined in O'Keeffe et al. (2016) in collaboration with the DBFZ (Deutsches Biomasseforschungszentrum) (Ponitka et al., 2015). Six biogas clusters with representative feedstock profiles for agricultural biogas plants were identified for the federal state of Saxony (Table 2). The biogas clusters were differentiated by installed capacity and for the capacity class 151–500 kW also by agro-economic region. For the other capacity classes, a regional differentiation was not possible due to data limitations. The representative feedstock profiles for each biogas cluster were used to generate the appropriate feedstock demand for each biogas plant based on their individual installed electrical capacities (kW_{el}). Manure and slurry have been merged to the feedstock class “animal excrement” using the differences in dry matter and carbon content of dry matter to be consistent with the calculation of available excrement (Section 2.2.3).

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